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Transport of low-energy electrons in non-degenerate n-InSb under longitudinal magnetic field

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Abstract. Longitudinal magnetoresistance of moderately doped n-InSb samples was measured at low temperatures down to 12 K and at magnetic field up to 4.8 kG. The samples remain non-degenerate down to the lowest temperature. Analyses were carried out for both the lattice and ionized impurity scattering regimes. Data were discussed in terms of possible contribution of the low-energy electrons towards the conductivity.

Keywords: indium antimonide, magnetic field, magnetoresistance.

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1. Introduction

The importance of the kinetics of electrons in magnetic fields is still receiving considerable investigations [1-3]. In lightly doped semiconductors, the impurity concentration is low, and the total energy states are formed in the forbidden band. Since the impurity atoms are far apart (their density is several orders of magnitude less than the density of atoms of the host material), there supposed to be no interaction between these impurity centers. Therefore, the carriers obey Boltzmann statistics (non-degenerate case).

In heavily doped semiconductors, the impurity concentration is high. In this case, the interaction of impurities cannot be neglected since the distance between impurity atoms is much smaller. The wavefunctions of electrons of neighboring impurity centers overlap, and the total energy levels broaden and form the impurity band that might merge with the conduction band. In this case, Fermi-Dirac statistics should be applied (degenerate case).

If the temperature (T) of a degenerate system is increased so that the condition of degeneracy ($E_F >> kT$) is no longer valid, then a non-degenerate state may be satisfied when $kT >> E_F$, although the impurity concentration remains unchanged, E_F here is the Fermi energy and k is the Boltzmann constant.

It is well documented that indium antimonide with an excess of donor centers does not exhibit thermal freeze-out of conduction electrons onto the donor centers as the temperature is reduced [4]. This is supposed to be a result of a large effective Bohr radius and vanishing donor activation energy so that donor levels merge completely with the conduction band. However, if a magnetic field is applied, the donor activation energy increases and the radius of the donor center decreases. For lower fields, the resistivity remains quasi-metallic, being independent (or weakly dependent) of temperature down to very low temperatures [4].

For moderately doped InSb with a typical impurity concentration of the order of 10^{14} cm^{-3}, the degenerate temperature is around 10 K. In this case, one may observe the intrinsic, lattice as well as the ionized impurity scattering mechanisms under non-degenerate conditions down to 10 K.

The extreme quantum limit in InSb is easily accessible. For the non-degenerate system, the condition required is that $\hbar\omega_c > kT$, where ω_c is the cyclotron frequency and $\hbar$ is the reduced Planck constant. Then defining $\beta = \hbar\omega_c / kT$ for InSb, $\beta = 5$ for $T = 20$ K and magnetic field of 6 kG. Using the closed cycle cryostat and the available magnetic field of about 5 kG, one may tune through the two regimes of lattice and impurity scattering mechanisms and may locate the sample in the near vicinity of the extreme quantum limit.

The failure of old theories [5] to reproduce the actual temperature and magnetic field dependence of both the resistivity tensors (transverse ρ_{xx} and longitudinal ρ_{zz}) and the arguments of Gusev *et al.* [1] and Murzin and Golovko [3] concerning the contribution of the low-energy electrons to the conductivity motivated the present study.

We describe here the temperature and the magnetic field dependences of the longitudinal resistivity for some moderately doped n-InSb in both the ionized impurity and lattice scattering regimes. The investigations were performed under non-degenerate conditions in the neighborhood of the quantum limit. The behavior of the transverse resistivity of this particular system was earlier studied [6].

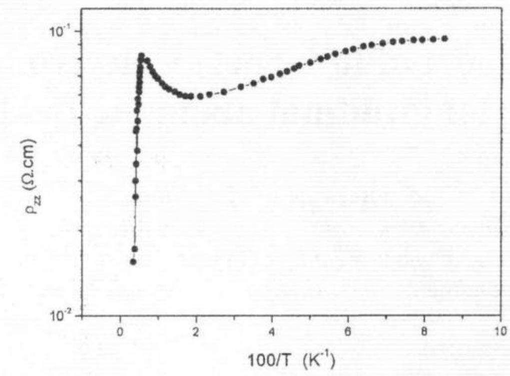

Fig. 1. Temperature dependence of the resistivity of the sample 3214 at zero magnetic field.

2. Experimental

Te-doped n-InSb samples (supplied by MCP electronic materials Ltd., Middlesex, England) were used in the present investigations. Presumably, doping was added during the crystal growth. Bar-shaped samples were prepared in dimensions of about $10\times1\times1$ mm^3. The samples (of carrier densities 1.8×10^{14} and 3.2×10^{14} cm^{-3} coded as 1814 and 3214) were etched in CP4 to remove surface damage and contamination. Four-probe technique was employed for the d.c. resistivity measurements using very low currents to avoid heating effects. A closed cycle cooler was used to achieve temperatures as low as 12 K and an electromagnet of 4.8 kG was applied parallel to the d.c. signal. Data were recorded at different magnetic fields in steps of 0.5 kG and up to the maximum available fields. The degenerate temperatures ($T_d = (3/\pi)^{2/3}(h^2/8m^* k_B)n^{2/3}$) for our samples were calculated using $m^* = 0.0145\ m_0$. They were found to be about 9 and 14 K for 1814 and 3214 samples, respectively. Obviously, the electron gas is degenerate below the calculated T_d.

3. Results and discussion

The typical temperature dependence of the resistivity ρ at zero magnetic field for the sample 3214 is depicted in Fig. 1. As our main interest is to investigate the behavior of ρ in both the lattice and impurity scattering regimes, we will restrict ourselves to the temperatures below 150 K. It is quite clear that, below about 150 K, two distinct regions can be distinguished; these are the well known lattice scattering down to about 50 K and the ionized impurity scattering which takes over below 40 K.

It is not surprising not to observe thermal freeze-out as that observed in n-InP [7]. The absence of this freeze-out is attributed to a complete mergence of the impurity band, for this particular material, with the bottom of the conduction band.

In what follows, the magnetic field dependence as well as the temperature dependence of ρ_{zz} will be discussed. The variation of the longitudinal resistivity with the magnetic field *B*, in both the ionized impurity and lattice scattering regimes for both samples is displayed in Fig. 2. No Shubnikov-de Haas oscillations were recorded in the present study. This confirms our original assumption that the samples are under non-degenerate conditions. Inspection of Fig. 2 shows that the magnetic field dependence of ρ_{zz} can be represented by a linear relationship. To a very good approximation, the slope of the straight lines (in both regimes) is 1.1.

The longitudinal resistivity ρ_{zz} under non-degenerate conditions, in the range of predominantly lattice scattering, is related to *B* and *T* by the relation

$$\left(\frac{\rho_{zz}}{\rho}\right)_L = \frac{n}{3n_B}\left(\frac{\hbar\omega_c}{kT}\right), \qquad (1)$$

where ρ is the resistivity in absence of the magnetic field, *n* and n_B are the concentrations of charge carriers in absence and presence of the magnetic field, respectively. Thus, for non-degenerate semiconductors in the extreme quantum limit the longitudinal magnetoresistance in the lattice scattering range should exhibit a linear dependence on the magnetic field (assuming a negligible dependence of n_B on *B*). This is in contradiction to the classical Boltzmann theory that predicts no magnetoresistance at all. The linear magnetic field dependence of ρ_{zz} is obtained in the present study, although the condition of extreme quantum limit is not entirely satisfied. Then, one may suggest that the above equation is applicable even below the extreme quantum limit.

When ionized impurity scattering is predominant, one has the relation

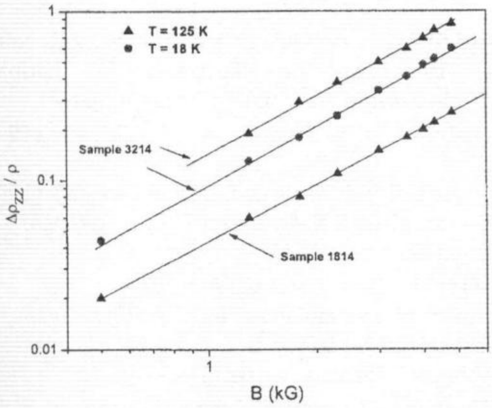

Fig. 2. Magnetic field dependence of $\Delta\rho_{zz}/\rho$ for the samples 3214 and 1814 at T = 18 K and T = 125 K.

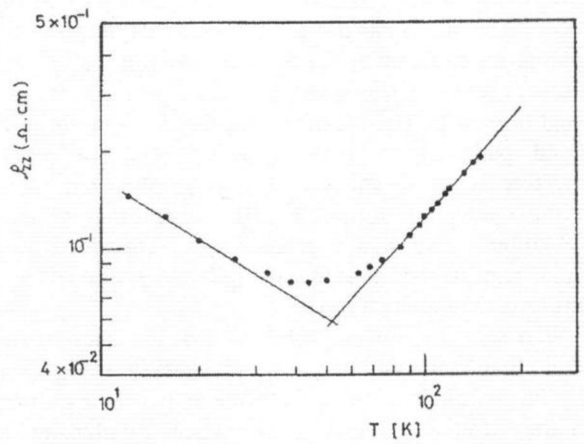

Fig. 3. Temperature dependence of ρ_{zz} for the sample 1814 at B = 4.42 kG in both the ionized impurity and lattice scattering regimes.

$$\left(\frac{\rho}{\rho_{zz}}\right)_I = \frac{\sigma_{zz}}{\sigma} = \left(\ln(1+b_o) - \frac{b_o}{1+b_o}\right)\times$$
$$\times\left(\frac{1}{2}+\frac{3}{4}\left[\frac{1}{b}\right]+\frac{3kT}{\hbar\omega_c}\left[2+\frac{4}{b}+\frac{3}{b^2}\right]\right) \qquad (2)$$

where $b = b_o(n/n_B)$ and $b_o = \frac{6}{\pi}\left(\frac{m^*(kT)^2}{n\hbar^2 e^2}\right)$.

Inspection of Eq. (2) reveals an interesting feature, namely: for values $b_o \geq 1$, the ratio $\frac{\rho}{\rho_{zz}} = \frac{\sigma_{zz}}{\sigma}$ may exceed unity. Thus, a possible negative magnetoresistance may be observed [8].

In the present study, b_o at $T = 20$ K (the middle of the impurity scattering regime) exceeds unity. Nevertheless, one cannot observe a negative magnetoresistance. It has been pointed out by many authors [8, 9] that the origin of the negative magnetoresistance, in the impurity scattering regime, comes from the effect of a strong magnetic field which might inhibit the small-angle scattering. This small-angle scattering is primarily responsible for momentum loss of the electron in the field-free case. Therefore, in presence of strong magnetic field, the scattering is reduced and a negative magnetoresistance occurs. As the optimum magnetic field in the present study is just around 5 kG, one then may not claim that the field is strong enough to inhibit the small-angle scattering. Then the absence of the negative magnetoresistance can be justified. The possible magnetoresistance of the barely metallic n-InSb samples (with $n > n_c$) strongly supports the importance of electron interactions for the barely metallic cases [10], n_c is the critical concentration at the metal-nonmetal transition.

Fig. 3 demonstrates the temperature dependence of ρ_{zz} for the sample 1814 at the magnetic field of 4.42 kG. Plots are given here for both the lattice and impurity scattering regimes. Very similar data were obtained for the other sample. The longitudinal resistivity ρ_{zz} varies with temperature as $T^{3/2}$ in the lattice scattering region, and this is very similar to the field-free case.

On the other hand, the temperature dependence of the longitudinal conductivity σ_{zz} in the case of ionized impurity scattering regime is approximately given by $\sigma_{zz} = \frac{1}{\rho_{zz}} \propto T$. Experimental observations, however, show that σ_{zz} is only weakly temperature dependent as $\sigma_{zz} = \frac{1}{\rho_{zz}} \propto T^{1/2}$ (see Fig. 3).

In the work by Murzin and Golovko [3], it has been pointed out that due to the contribution of the low energy electrons to the transverse conductivity the temperature dependence of the conductivity takes the form $\sigma_{xx} \propto T^{9/8}$ rather than $T^{3/2}$ as originally predicted by Adams and Holstein [5]. The reduction in the power of the temperature dependence of σ_{zz} in the present study is thought then to be due to a possible contribution of the low-energy electrons, which might be still effective even for the case of the longitudinal configuration. The $T^{9/8}$ – dependence predicted by Murzin and Golovko was obtained using the assumption of the presence of large-scale potential fluctuation in the material. It may be argued that the randomly-non-homogeneous non-correlated impurity distribution in the investigated samples would lead to such fluctuation of the potential. Detailed measurements, in a wide range of concentrations by using other systems, may be of great interest to understand the minimum magnetic fields down to which the contribution of low-energy electrons is still effective. It has to be mentioned that, in presence of large-scale potential fluctuations, the motion of the current charge carriers in the electric field is not straightforward. These carriers are forced to go through curved paths round the humps of potential relief. Therefore, there are various orientations of current paths in this potential relief. In 3D case, the various orientations have equal probabilities. Therefore, one would expect the absence of pure longitudinal and transverse magnetoresistance.

To sum up, the magnetic field dependence of the longitudinal resistivity under non-degenerate statistics is of a linear relationship in both the lattice and ionized impurity scattering regimes. This linear relationship is already reported for the case of the transverse resistivity, if the contribution of the low-energy electrons towards the conductivity is considered. The reduction in the power of the temperature dependence of ρ_{zz} may be attributed to the low-energy electrons.

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